

NUMERICAL MODELING OF PLATE MOTION: UNRAVELING EUROPA'S TECTONIC HISTORY.

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Introduction: Europa is a highly fractured body broken into plates that have rotated with respect to one another. The effect of these rotations can be seen as regions of extension, strike-slip motion, and possibly compression [1,2,3,4]. Various authors have tried to reconstruct a number of these regions in an effort to gain a better understanding of the tectonic history of the icy satellite [4-8].

The typical approach used to determine a best-fit reconstruction could be described as a 'cut-and-paste' method in which the plates in an image are manually separated and reoriented in an effort to reconstruct preexisting features [4,5,6]. Some authors subsequently determined poles of rotation for the regions reconstructed [7,8]. This step is essential to determining the validity of a reconstruction when the size of a region is such that the curvature of the satellite cannot be ignored.

In those cases that have looked for a pole of rotation, a forward approach is typically used. This method can be used to show that the reconstruction produced has a unique solution but it cannot tell whether or not there were other unique solutions that were not considered. Here we report on the development of an inverse method for determining the Euler pole of a region that has undergone rotation. This method can be used to test all possible rotations of the region and therefore determine all unique solutions (if they exist).

The Model. The inverse model we have developed uses an iterative grid-search method to find an Euler pole of rotation for the region to be reconstructed such that ridges cut and offset will be realigned. The result is a minimized best-fit pole with confidence regions. This is a brute force method that is mathematically simple but computationally cumbersome. The computational requirements of this modeling technique limit the resolution of the grid that can be used to determine the Euler pole but it is sufficient to fully resolve the pole for the resolution of the image used.

$$\begin{aligned} N_x &= (A_y * B_z - A_z * B_y) / \sin \delta \\ N_y &= (A_z * B_x - A_x * B_z) / \sin \delta \\ N_z &= (A_x * B_y - A_y * B_x) / \sin \delta \\ \delta &= \cos^{-1} (A_x * B_x + A_y * B_y + A_z * B_z) \end{aligned} \quad (1)$$

The model uses two points (A and B) on a fixed plate to form a plane through the body (Fig. 1). The normal to that plane is determined using equation 1 and the distance from that plane to a point (C) on the plate to be reconstructed that corresponds to the offset feature of the fixed plate is determined using equation 2.

$$dist = \left| \overline{AC}_x * N_x + \overline{AC}_y * N_y + \overline{AC}_z * N_z \right| \quad (2)$$

A best-fit reconstruction of the points described involves rotating point C on the plate to be reconstructed about an Euler pole such that it falls in the plane of points A and B on the fixed plate. To accomplish this we use a rotation matrix (equation 3), where R_{ij} is the rotation matrix and it is defined by an Euler pole $E = (E_x, E_y, E_z)$ and an angle of rotation Ω [9].

$$\begin{bmatrix} C_{x'} \\ C_{y'} \\ C_{z'} \end{bmatrix} = \begin{bmatrix} R_{11} & R_{12} & R_{13} \\ R_{21} & R_{22} & R_{23} \\ R_{31} & R_{32} & R_{33} \end{bmatrix} * \begin{bmatrix} C_x \\ C_y \\ C_z \end{bmatrix} \quad (3)$$

Confidence regions for the determined pole were calculated using the following equation [10]:

$$R = R_{\min} \left(1 + (N / M - N) F[N, M - N, 1 - \alpha] \right)^{1/2} \quad (4)$$

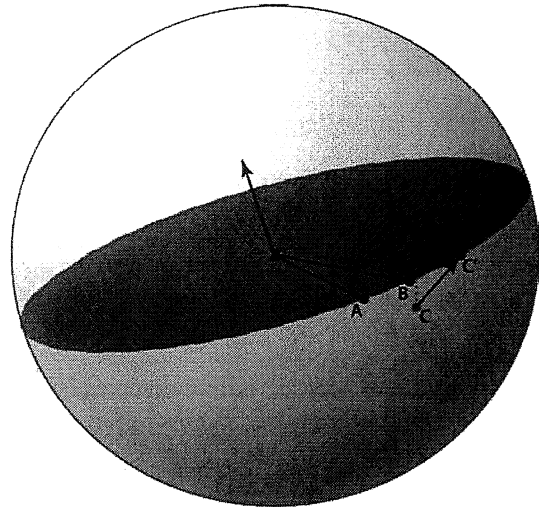


Fig. 1. Illustration of inverse modeling technique. A and B represent points on an offset feature lying on a fixed plate and C represents a point on the same offset

feature lying on the plate to be rotated. C' represents the position of the offset feature after rotation.

A Test Case: The Castalia Macula region was chosen as a test case for the application of this inverse method (Fig. 2). The region in the image is centered about the equator and spans ~ 800 km. We rotated one plate in this region that is marked by numerous offset features, 27 of which were used in this analysis (the main criterion for choosing these features was clarity of the precise location of each feature across the plate boundary).

The model determined the Euler pole that minimized the distance between the offset features after iterating through every possible combination of pole location and rotation. The resolution of the grid used was increased steadily until we reached the resolution limit of the image. Figure 3 indicates the location of the best-fit pole for this region. The final grid employed was a $1^\circ \times 1^\circ$ latitude/longitude grid with possible rotations tested ranging from -1° to 1° in $.01^\circ$ increments. The pole location is 11° lat. and 253° lon. with -0.43° rotation and the post reconstruction misfit of previously offset features for this reconstruction is within the resolution of the image. This, along with the tightly constrained confidence regions, indicates that a best-fit Euler pole for the region in question has been determined.

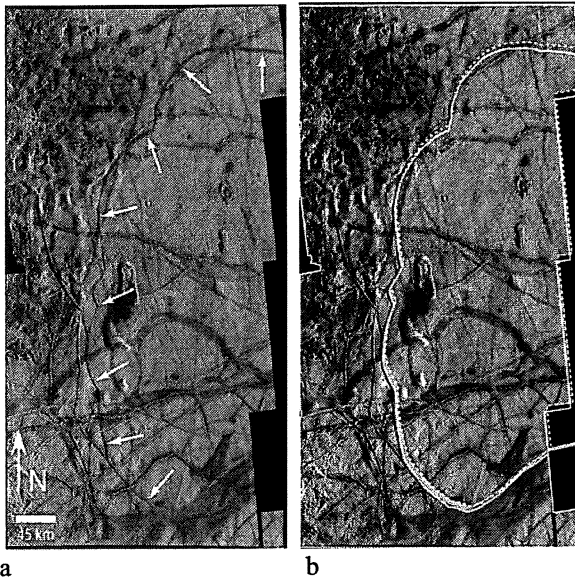


Fig. 2. Castalia Macula region (centered at $\sim 0^\circ$ lat and 227° lon) as seen in Galileo E17REGMAP01 mosaic (a). Image is transmercator projected with resolution of 220m/pix. Arrows indicate ridge that was reconstructed. Reconstruction of region (b) using Euler pole and rotation shown in Fig. 3. Solid line indicates position of plate before reconstruction and dashed line indicates position after.

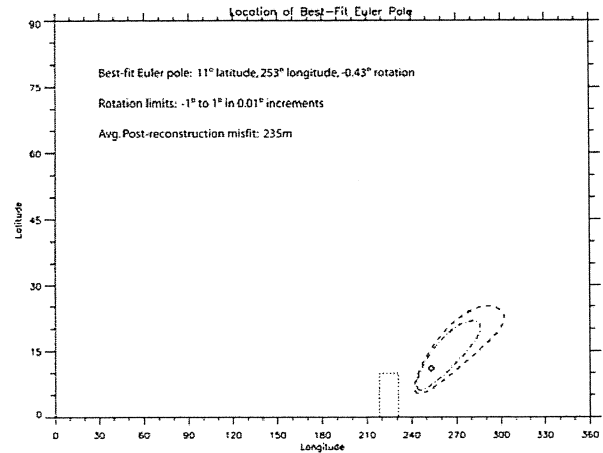


Fig. 2. Plot indicating position of best-fit Euler pole for Castalia Macula region. Dashed lines represent 95% and 99% confidence regions.

Conclusions and Implications: The test case for this method demonstrates that a unique solution for the Euler pole of rotation of this region can be determined. Knowledge of this unique solution allows us to produce a reconstruction of the plate motion in this region with an accuracy that can be quantified. Application of this method to other regions could provide a powerful means of unraveling the tectonic history of Europa.

The application of this model is presently limited by the spatial resolution and coverage available from the Voyager and Galileo missions. Increased image resolution and global comprehensive coverage by future missions will allow us to constrain pole locations and degree of rotation with increased accuracy as well as to consider the broader implications of regional plate rotations on Europa's global tectonic history.

Acknowledgements: We would like to thank Donald Forsyth for his assistance in developing the inverse model.

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